*International Research Journal of Environmental Sciences*_____ ISSN 2319–1414
Vol. **15(2),** 54-66, April **(2026)** *Int. Res. J. Environmental Sci.*

Review paper

Review status of High Background Radiation Area (HBRAs) associated with Marine Microorganisms using Radioactive Remediation

Kumar Pandion
Center for Environmental Nuclear Research, Directorate of Research SRM Institute of Science and Technology, Kattankulathur, TN, India
kumarpandion@gmail.com

Available online at: www.isca.in, www.isca.me
Received 6th February 2026, revised 14th March 2026, accepted 9th April 2026

Abstract

The present study critically evaluates environmentally occurring High Background Radiation Areas (HBRAs) and their ecological association with marine microorganisms involved in radionuclide remediation. Emphasis is placed on the radiological characterization of environmental matrices, including seawater and coastal sediments, and the corresponding structure and functional diversity of microbial communities inhabiting these radiation enriched ecosystems. Microorganisms residing in HBRAs exhibit pronounced radio resistance and metabolic plasticity, enabling survival under chronic exposure to be elevated ionizing radiation. Such resilience is attributed to enhanced DNA repair systems, antioxidant defense mechanisms, efficient reactive oxygen species (ROS) scavenging, and adaptive genomic modifications. Long-term radiation exposure has driven selective pressure, resulting in stable genetic mutations and regulatory adaptations that optimize survival and metabolic efficiency in radionuclide-rich environments. Importantly, these adaptive traits facilitate diverse biogeochemical processes including bioaccumulation, biosorption, biotransformation, bio reduction, and biomineralization of radionuclides. Microbial taxa capable of mediating redox transformations can alter radionuclide speciation, solubility, and mobility, thereby promoting immobilization or detoxification. Additionally, certain strains possess metalbinding proteins, extracellular polymeric substances (EPS), and enzymatic systems that enhance radionuclide sequestration and precipitation. The sustained exposure of microbial communities to radionuclides in HBRAs provides a natural model system for understanding microberadionuclide interactions at molecular and ecosystem levels. This evaluation synthesizes current knowledge on physiological, biochemical, and genomic mechanisms underpinning microbial adaptation and highlights their potential application in developing sustainable, eco-compatible strategies for radioactive waste remediation and environmental restoration.

Keywords: HBRA, Microorganisms, Radionuclides, Remediation**.**

Introduction

High Background Radiation Areas (HBRAs) are geographically distinct regions characterized by elevated levels of natural ionizing radiation compared to global background averages[1]. The enhanced radioactivity in these regions is primarily controlled by geological and geochemical factors, particularly the presence of radionuclide bearing minerals such as monazite and other thoriumand uraniumrich deposits[1]. Prominent HBRAs have been reported in China, Brazil, Iran, France, and India[1]. Many of these areas are in coastal, arid, or semi-arid zones were mineralogical processes favor radionuclide accumulation. In certain coastal regions of Brazil, particularly along monaziterich black sand beaches, elevated external gamma dose rates have been recorded. Radiation levels in these regions may reach approximately 5µGy h^{-1}, nearly 400 times higher than the average background radiation levels in the United States[2]. The Brazilian beach sands contain complex radionuclide bearing mineral assemblages in addition to non-radioactive minerals, contributing to heterogeneous radiation exposure profiles[2].

Radiobiological investigations conducted in HBRAs provide a unique opportunity to evaluate the long-term biological and ecological effects of chronic radionuclide exposure under natural conditions. These environments function as natural laboratories for assessing adaptive responses in resident organisms, including microorganisms exposed to persistent ionizing radiation stress. Bioremediation applications in marine biotechnology, using either whole microbial cells or their metabolites, are diverse. Microorganisms belonging to the phyla Actinobacteria, Proteobacteria, Bacteroidetes, Cyanobacteria, and Firmicutes have demonstrated the ability to degrade recalcitrant organic pollutants such as polycyclic aromatic hydrocarbons (PAHs)[2,3]. In oil contaminated sediments and petroleum spill sites, these microbial communities exhibit substantial biodegradation potential for various hydrocarbons, aromatic compounds, and complex organic substrates[3]. Additionally, fungi capable of producing ligninolytic enzymes are employed in the removal of heavy metals from sediments, while molds producing oxidative enzymes are applied in the treatment and decolorization of highly colored industrial effluents[4,5].

Microbial diversity that has evolved under extreme environmental conditions is increasingly being explored for the remediation of radioactive contamination. These microorganisms offer several advantages, including environmental compatibility, operational simplicity, metabolic versatility, and minimal generation of secondary pollutants[6] . Many species can function independently under radionuclide stress, mediating redox transformations and immobilization processes. This report focuses on the distribution of microorganisms in radionuclide enriched environments, the mechanisms involved in their survival, and their adaptive responses to radiation exposure. Emphasis is placed on interactions between microbial cell walls and radioisotopes, which play a crucial role in bioremediation processes. This article further explains how marine microorganisms contribute to radionuclide removal, as well as how they influence radionuclide mobility, toxicity, and transport within HBRA ecosystems.

High background radiation areas (HBRAs)

HBRAs of various portions of the world: Brazil represents one of the earliest and most extensively investigated regions of naturally occurring High Background Radiation Areas (HBRAs), with systematic research initiated in the mid-1970s[7] . Major HBRA regions in Brazil include Araxá, Poços de Caldas, Tapira, and the coastal area of Guarapari, located within Minas Gerais and Espírito Santo States[7] . These regions are geologically associated with volcanic and alkaline complexes enriched in uranium- and thorium-bearing minerals. Guarapari, situated along the Atlantic coast of Espírito Santo State, is particularly well known for its monaziterich black sand beaches[8-10]. Approximately 12,000 residents inhabit areas adjacent to these monazite deposits, which constitute significant sources of external gamma radiation and alpha emitting radionuclides. Radiation exposure levels in certain locations have been reported to exceed the global average background radiation by nearly threefold[7] . The Brazilian HBRA has therefore served as an important natural laboratory for longterm radiobiological investigations[1,12,13].

Comparative investigations have also been conducted in China's Yangjiang HBRA, including collaborative studies between Chinese and Japanese researchers. In Yangjiang, the mean annual internal effective dose from natural radiation sources has been estimated at approximately 4.27 mSv for residents living within the HBRA region[14,15]. These findings provide critical insights into chronic low-dose radiation exposure and associated biological responses. Another globally significant HBRA is in Ramsar, northern Iran, situated along the Alborz (Elburz) Mountains adjacent to the Caspian Sea[16,17]. Ramsar is recognized both as a biodiversity-rich region and as one of the highest natural radiation areas in the world. Elevated radiation levels in certain residential zones are attributed to high concentrations of ^{226}Ra in building materials, increased ^{222}Rn (radon) exhalation, and enhanced indoor and outdoor gamma radiation exposure[7] . The Ramsar region contains nine geothermal springs with varying radium concentrations, contributing to spatial heterogeneity in radiation dose distribution[18] . Table-1 presents a comparative overview of radioactivity levels reported in major HBRAs worldwide.

Table-1: Annual Outdoor Gamma Radiation Dose Levels Reported in Different Countries

Location	Annual Effective Dose (mSv y^{-1})	Reference
Bangladesh	2.0 (1.0–3.9)	8
Japan	0.48	9
Ireland	0.55	10
Netherlands	0.58	11
United Kingdom	0.31–0.61	12
Petralona Cave, Greece	0.19–0.67	13
Taiwan	0.50	14
Hong Kong	1.11	15
Iraq	0.39	16
China	0.42	17

HBRAs of various parts of the India: India hosts significant monaziterich placer deposits along approximately 57 km of coastline spanning Kerala, Tamil Nadu, Andhra Pradesh, and Odisha. These deposits contain elevated concentrations of naturally occurring radionuclides, particularly thorium (^{232}Th) and uranium (^{238}U), making them among the most important High Background Radiation Areas (HBRAs) globally[19]. Extensive monitoring studies conducted in the former South Travancore region, which includes parts of Kerala and the Kanyakumari district of Tamil Nadu, have documented enhanced natural radiation levels associated with monazite-bearing coastal sands. Residents of several villages within the Karunagappally administrative region of Kerala are exposed to higherthan global average natural radiation doses due to the presence of thorium enriched soils within the monazite belt. This region is recognized as one of the world's well-characterized HBRAs[19]. The local population has inhabited these areas for more than 20 generations, experiencing chronic exposure to elevated natural radionuclide levels throughout their lifetime[19] .

The coastal stretch of Kerala, extending from Neendakara village in Kollam district to Purakkad village in Alappuzha district, represents one of the most densely populated HBRA zones in India[20] . This region has been continuously inhabited

for over a millennium, providing a unique demographic setting for longterm radiobiological and epidemiological investigations. In southern Tamil Nadu, the Manavalakurichi coastal region is characterized by highly abundant heavy mineral deposits, including monazite. Elevated and spatially variable radionuclide concentrations have been reported in this area[21]. Additional inland districts of Tamil Nadu, including Dharmapuri, Vellore, Krishnagiri, and Salem, have also shown notable uranium and thorium occurrences, as documented by Bhattacharya[22].

A newly investigated high natural radionuclide zone has been reported in a thermal region of the Eastern Ghats, India, where sediment analyses revealed concentrations of approximately 95 ppm of ^{238}U, 1194 ppm of ^{232}Th, and 4% of ^{40}K[23]. Similarly, the Chhatrapur coastal placer deposits in Odisha are recognized as HBRA regions, exhibiting radiation levels above global averages[24] . In Andhra Pradesh, the Koppunuru uranium deposit, hosted in primary rock formations near the Chenchu tribal settlement, represents a significant uranium mineralization zone[25] . Furthermore, elevated uranium concentrations have been reported in the Lambapur and Peddagattu areas of the Nalgonda district[26] . These regions are under consideration for uranium mining activities, and baseline radiological assessments are considered essential prior to large-scale extraction operations[26] .

Radioactivity in the different environmental matrixes

Water: Water intended for human consumption must undergo appropriate treatment, as raw water sources may contain suspended particulates, dissolved chemical constituents, microbial contaminants, and naturally occurring radionuclides that pose potential health risks. The concentration of dissolved natural radionuclides in raw water is largely influenced by the specific activity of radionuclides present in surrounding geological formations and sediments, as well as the extent of waterrock interaction processes such as weathering, leaching, and ion exchange[27] . Hydrogeochemical conditions including pH, redox potential, salinity, and residence time play a critical role in governing radionuclide mobility and solubility. During water treatment processes, radionuclides may be partially removed through coagulation, filtration, adsorption, or precipitation, often resulting in their accumulation within treatment residuals and by-products[27] .

Uranium concentrations in marine waters are generally considered to be relatively homogeneous on a global scale due to its conservative geochemical behavior and long residence time in seawater[28] . However, localized variations may occur in proximity to mineralized zones or coastal HBRA regions. The detection and quantification of radionuclides such as ^{238}U, ^{232}Th, and ^{40}K in water samples across different seasons have been widely reported. Seasonal monitoring studies have demonstrated variability in radionuclide concentrations depending on hydrodynamic conditions, sediment resuspension, and freshwater inputs[29,30] . Vegueria et al. measured radium concentrations in multiple seawater samples collected along the Brazilian coastline and reported spatial variability associated with coastal geological characteristics[29,30] . Such findings highlight the importance of continuous radiological monitoring in HBRA associated marine environments to assess radionuclide transport, dilution, and potential ecological exposure pathways.

Sediment: Sediments play a fundamental role in aquatic ecosystems, functioning both as sinks and secondary sources of radionuclides. Therefore, detailed radiological assessment of marine and coastal sediments is essential for effective environmental monitoring, risk evaluation, and sustainable management of marine resources[31]. Radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K have been extensively analyzed in sediment samples collected from the eastern coast of Tamil Nadu. The average activity concentrations of ^{232}Th and ^{40}K were reported to be significantly higher than global mean values, whereas ^{226}Ra levels were comparatively lower than the worldwide average[32].Comprehensive radiological investigations of Kerala's coastal sediments have evaluated the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K along with eight derived radiological hazard indices to assess potential radiation risk. In several sampling locations, the measured concentrations of ^{238}U and ^{232}Th, as well as associated radiological parameters such as absorbed dose rate, radium equivalent activity (Raeq), external hazard index (Hex), and annual effective dose, exceeded recommended global reference values[33]. These findings confirm the classification of parts of the Kerala coastline as High Background Radiation Areas (HBRAs).

The occurrence of uranium in marine sediments, including studies conducted in the North Sea region, has also been discussed by Ramasamy[33], highlighting the geochemical controls influencing uranium distribution in marine depositional environments. Naturally occurring and anthropogenic radionuclides preserved within seabed sediments provide valuable information regarding sediment transport dynamics, vertical accretion rates, depositional history, and large-scale geochemical cycling processes[34] . Consequently, sediment radioactivity serves as an important tracer for understanding both environmental risk and sedimentary evolution in coastal HBRA regions.

Close attention between microorganism and radionuclides

Sediment dwelling microorganisms exert significant influence on biogeochemical cycling processes, facilitating the transfer and transformation of conserved elements between biotic and abiotic compartments of aquatic ecosystems[35] . Through their metabolic activities, these microorganisms regulate the speciation, mobility, and partitioning behavior of radionuclides within sediment water interfaces. To better understand these interactions, the concepts of bioavailability and bio accessibility are critical. Radionuclide bioavailability in sediments is

commonly evaluated using the solid liquid distribution coefficient (Kd), which represents the partitioning of a radionuclide between the solid phase (sediment) and the aqueous phase[36] . Mathematically, Kd (expressed in L kg^{-1}) denotes the ratio of radionuclide activity concentration adsorbed onto sediment (Bq kg^{-1} dry weight) to that dissolved in the aqueous phase (Bq L^{-1}). The Kd value functions as an important geochemical parameter controlling radionuclide mobility and biological uptake potential in aquatic environments[36] .

Assessment of radionuclide bioavailability in both sediment and overlying water is therefore essential, as the migration of radioactive cations is often restricted by strong adsorption to sediment particles and mineral surfaces[37] . The 5th European Framework Program project BORIS (Bioavailability of Radionuclides in Soils) provided comprehensive evaluation of physicochemical and biological parameters influencing radionuclide microorganism interactions in sediment and aquatic systems[37]. The project emphasized that radionuclide bioavailability is a dynamic property governed by mineralogy, redox conditions, organic matter content, and microbial activity. When radio nuclides interact with microbial cells, processes such as adsorption, enzymatic transformation, and intracellular sequestration may alter radionuclide speciation and decay pathways[38] . Microbial biomass is known to exhibit strong affinity for radioactive elements due to the presence of functional groups (carboxyl, phosphate, hydroxyl, and amino groups) within cell wall polymers and extracellular polymeric substances (EPS)[39] . This affinity underpins the application of microorganisms in radionuclide removal and immobilization strategies.

Although microbial interactions with radio nuclides share similarities with metal mineral geochemical reactions, biological systems introduce additional mechanisms driven by metabolic activity. The fundamental processes involved include biotransformation, biosorption, bioaccumulation, bioprecipitation, and bio solubilization, which collectively govern radionuclide mobility and stabilization in the environment. These mechanisms form the conceptual framework for microbial radionuclide bioremediation and are discussed in detail in the following sections (Figure-1). Schematic representation of major biotechnological approaches involved in microbial bioremediation of radionuclides.

Bioaccumulation: Bioaccumulation refers to the progressive uptake and intracellular retention of a substance within a biological organism over time[40]. In the context of radionuclides, bioaccumulation results from both bioconcentration (direct uptake from the surrounding medium) and biomagnification (increase in concentration across trophic levels). At the microbial level, radionuclide bioaccumulation is initiated by electrostatic interactions between positively charged radionuclide cations and negatively charged functional groups present on the microbial cell surface. These functional groups primarily carboxyl, phosphate, hydroxyl, and sulfhydryl moieties embedded within peptidoglycan, teichoic acids, and extracellular polymeric substances (EPS) facilitate initial surface binding through electrostatic attraction and ion exchange mechanisms.

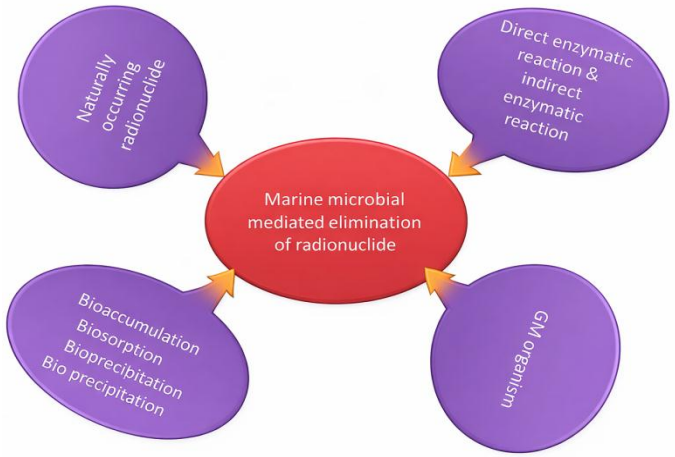

Figure-1: Summarization of various biotechnological approaches for bioremediation of radionuclides.

According to Staunton[40] , bioaccumulation may occur through either passive (energy independent) or active (energy dependent) processes. Passive uptake is typically governed by diffusion and electrostatic adsorption, whereas active uptake involves specific membrane bound transport systems that translocate radionuclides or chemically analogous ions into the cytoplasm. Once internalized, radionuclides may be sequestered within intracellular compartments, bound to proteins, or incorporated into metabolic pathways via metal transporter systems[41]. Experimental studies have demonstrated enhanced radionuclide uptake under metabolically active conditions. For example, the accumulation of iodide by sediment associated *Bacillus subtilis* increased significantly following glucose supplementation, indicating energy dependent transport activity. Furthermore, *Bacillus vallismortis* has been reported to bioaccumulate uranium (VI) at an initial concentration of 5 mg L^{-1}, achieving uptake levels of approximately 50 mg g^{-1} (U per g dry biomass) after 72 hours of incubation. Quantification was performed using UVVis's spectrophotometry[42].

Grampositive bacteria such as *Bacillus subtilis*, *Micrococcus luteus*, and *Bacillus megaterium* exhibit notable capacity for thorium sequestration from aqueous solutions, thereby reducing thorium and uranium mobility in contaminated environments[43]. The efficiency of radionuclide bioaccumulation depends on multiple factors, including radionuclide speciation, oxidation state, ionic radius, and charge, as well as microbial cell wall composition, surface charge density, and metabolic activity. Because bioaccumulation involves rapid interaction between radionuclides and anionic functional groups on the microbial cell surface, the process is strongly influenced by both physicochemical characteristics of the radionuclide and intrinsic biological properties of the microorganism.

Bio sorption: Biosorption refers to the physicochemical sequestration of positively charged metal or radionuclide ions onto negatively charged functional groups located on microbial cell membranes and extracellular polysaccharides[44]. This process is predominantly a passive, metabolism independent mechanism and occurs primarily at the cell surface through electrostatic attraction, ion exchange, complexation, and coordination interactions. Biosorption may proceed through either direct or indirect pathways. In direct biosorption, radionuclide ions bind immediately to functional groups such as carboxyl, phosphate, hydroxyl, amino, and sulfhydryl moieties present in cell wall polymers. Indirect biosorption may involve modification of the surrounding microenvironment through microbial metabolites that enhance metal precipitation or adsorption. The often-irreversible association of radionuclides with structural cell wall components is attributed to strong ligand binding and coordination interactions and is generally considered an inert or non-metabolically driven uptake mechanism[45].

Extracellular polymeric substances (EPS) produced by microorganisms play a crucial role in radionuclide sequestration. For example, extracellular materials derived from *Rhodococcus opacus* and *Rhodococcus rhodochrous* have been shown to effectively sorb Cd (II), Pb (II), Ni (II), Co (II), and Cr (VI) ions, resulting in the formation of insoluble complexes[46]. These extracellular biopolymers contain multiple reactive functional groups capable of binding divalent and multivalent metal cations through electrostatic and chemical interactions. The efficiency of biosorption is influenced by several parameters, including pH, ionic strength, competing cations, radionuclide speciation, and the density of reactive binding sites on the microbial surface. Rapid saturation of available binding sites may occur when multiple cations compete for the same irreversible adsorption locations on the cell wall. Furthermore, competitive desorption processes may be induced by excess cations with higher binding affinity, thereby affecting sorption stability and reversibility[47]. Overall, biosorption represents a rapid and effective mechanism for radionuclide immobilization and is widely regarded as a promising strategy for the remediation of radioactive contaminants in aquatic and sedimentary environments.

Biotransformation: Microbial metabolic processes can induce significant alterations in the speciation, valence state, mobility, and bioavailability of radionuclides in environmental matrices. One of the primary mechanisms governing these transformations is microbially mediated redox reactions, which directly influence radionuclide solubility and environmental behavior[48]. Changes in redox potential (Eh) and pH conditions often regulated by microbial respiration and metabolic byproducts play a decisive role in controlling radionuclide partitioning between dissolved and solid phases. Microbial modification of radionuclides frequently results in the formation of oxides, reduced mineral phases, or insoluble precipitates. Certain microorganisms can utilize oxidized radionuclides, such as uranium (U(VI)), as terminal electron acceptors during anaerobic respiration. In such processes, soluble U(VI) is enzymatically reduced to U(IV), which has significantly lower solubility and tends to precipitate as uraninite (UO_2), thereby decreasing its mobility in groundwater and sediment systems[48].

Similarly, oxidized radionuclides such as neptunium (Np(V)) may undergo anaerobic bio reduction in the presence of suitable electron donors, including pyruvate or citrate, under proton-rich conditions. This transformation leads to the formation of less soluble mineral phases through biomineralization pathways[49]. Because reduced forms of radionuclides generally exhibit lower aqueous solubility, microbial reduction processes play a critical role in immobilization and long-term stabilization of radioactive contaminants.However, the effectiveness of such biotransformation pathways is often constrained by environmental conditions, particularly the requirement for strictly anaerobic microorganisms in many reductive processes[50]. Oxygen intrusion, fluctuating redox conditions, and competing electron acceptors may limit sustained radionuclide reduction in natural systems. Despite these challenges, microbially mediated redox transformations significantly enhance the feasibility of in situ bioremediation strategies for radionuclide contaminated wastes. By promoting immobilization through reduction and mineral precipitation, microbial systems can substantially reduce radionuclide transport and ecological exposure[50].

Biosolubilization: Biosolubilization refers to the microbially mediated mobilization of radionuclides and associated metals from solid matrices into aqueous phases through autotrophic metabolic processes. This mechanism is particularly relevant in environments where radionuclides are incorporated within mineral lattices or sulfide-bearing ores. During chemolithoautotrophic metabolism, microorganisms oxidize ferrous iron (Fe^{2+}), metal sulfides, and other reduced inorganic substrates, thereby generating acidic conditions that enhance mineral dissolution and radionuclide release[51]. Effective biosolubilization typically requires acidic pH, adequate moisture content, and the presence of molecular oxygen (O_2) to sustain oxidative metabolism. Many of the microorganisms involved are mesophilic to moderately thermophilic acidophiles that thrive in low-pH environments. Notably, genera such as *Sulfolobus* and *Acidithiobacillus ferrooxidans* have been extensively reported for their capacity to solubilize metal bearing minerals, including uranium-containing phases[51]. These microorganisms derive metabolic energy from the oxidation of Fe^{2+} and reduced sulfur compounds, producing sulfuric acid and ferric iron (Fe^{3+}), both of which promote oxidative dissolution of mineral matrices.

In applied systems, biosolubilization is often integrated with physical, chemical, and hydrometallurgical pretreatment processes. The combined application of acidic solutions,

microbial inoculation, and an appropriate inorganic energy source enhances leaching efficiency in uranium bearing ores and radioactive waste matrices[5 1]. This synergistic approach facilitates the release of radionuclides previously immobilized within solid phases. Under conditions of elevated salinity and phosphate availability, complexation reactions further influence radionuclide mobility. For example, uranyl (UO_2^{2+}) can form soluble uranylcitrate complexes consisting of multiple dissociated species. However, such complexation may also lead to secondary precipitation of uraniumcitrate phases under certain geochemical conditions, thereby limiting long-term mobility. In this context, citrate functions as a transient complexing agent, exerting a secondary or modulatory role in the biosolubilization process[5 2].Overall, biosolubilization enhances radionuclide mobility through mineral oxidation and complexation reactions, thereby playing a dual role in environmental systems facilitating both contaminant dispersion and, under controlled conditions, resource recovery or engineered remediation.

Bio precipitation: Radionuclides and associated metal elements are frequently immobilized in environmental systems through precipitation as carbonate, hydroxide, or oxide phases. Microorganisms play a pivotal role in this process by modifying local geochemical conditions and producing reactive ligands that facilitate mineral nucleation and growth[53]. Microbially derived extracellular polymeric substances (EPS), organic acids, and functional groups (e.g., carboxyl, phosphate, and hydroxyl moieties) act as nucleation sites, promoting the formation of stable mineral phases that incorporate radionuclides. Microbial metabolism significantly influences localized pH and redox potential (Eh), thereby altering radionuclide speciation and solubility. Variations in metabolic activity can generate microenvironments with elevated alkalinity or reducing conditions, favoring the precipitation of radionuclides as insoluble hydroxides or carbonates. Even subtle shifts in pH or Eh at the cellmineral interface may substantially affect radionuclide partitioning and mineral stability[53]. Such microscale geochemical gradients are critical in determining whether radionuclides remain mobile or become sequestered within solid phases.

Coprecipitation represents an additional immobilization pathway in which radionuclides are incorporated into forming mineral matrices during the precipitation of major metal oxides or carbonates[54]. In this process, radionuclide ions substitute for structurally compatible cations within the crystal lattice or become entrapped within amorphous precipitates. This mechanism enhances long-term stabilization, as radionuclides become structurally bound rather than merely adsorbed on mineral surfaces. Overall, microbially mediated precipitation and coprecipitation processes contribute significantly to the attenuation of radionuclide mobility in sediment and aquatic systems. These mechanisms are strongly governed by microbial metabolic rates, ligand production, and localized physicochemical gradients. Figure-2 summarizes the principal interaction pathways between radionuclides and microorganisms, including biosorption, bioaccumulation, biotransformation, biosolubilization, and bioprecipitation.

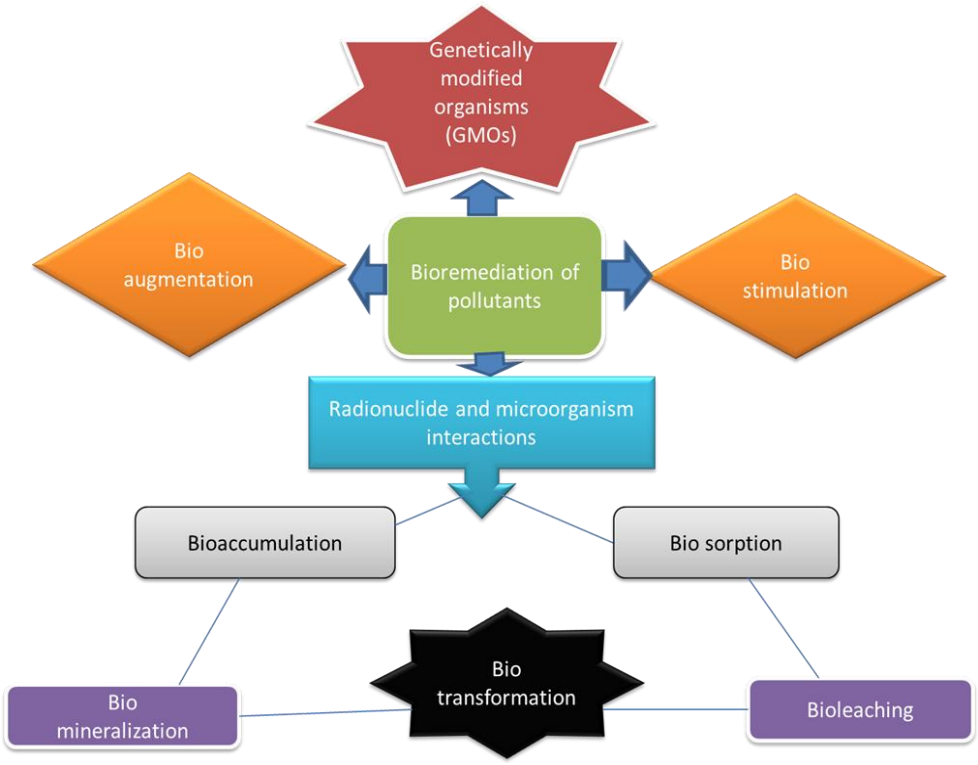

Figure-2: Summarization of radionuclide and microorganism interactions.

Miscellaneous: Microorganisms synthesize a diverse array of biopolymers, including *melanins*, *pyomelanin*, and related extracellular compounds, which have been shown to significantly influence radionuclide mobility and sequestration[55]. These biopolymers contain abundant functional groups (e.g., phenolic, carboxylic, and quinone moieties) capable of complexing metal ions and radionuclides, thereby altering their solubility, redox behavior, and environmental transport. The chelating and redoxactive properties of melanin-like substances enable them to act as both sorbents and electron shuttles in radionuclide transformation processes. Certain melanized fungi exhibit remarkable tolerance to ionizing radiation and, in some cases, enhanced growth under radioactive exposure. For instance, *Cryptococcus neoformans*, *Wangiella dermatitidis*, and *Cladosporium sphaerospermum* have demonstrated increased biomass production following exposure to ionizing radionuclides[55]. This phenomenon has been attributed to the radioprotective and potentially radio trophic properties of melanin, which may facilitate energy transduction or mitigate oxidative stress induced by radiation. In bacterial systems, *siderophore* production constitutes another important mechanism influencing radionuclide behavior. *Pseudomonads* produce a range of siderophoreslow molecular weight, high affinity chelating agents primarily involved in iron acquisition that can also bind actinides and other radionuclides. Notably, *pyoverdin*, a *fluorescent siderophore* produced by *Pseudomonas grimontii*, has been quantitatively characterized for its metalbinding capacity. Experimental investigations have further demonstrated significant sorption and complexation activity in *Pseudomonas fluorescens* and *Pseudomonas stutzeri* in the presence of radionuclides such as $^{\wedge 147}$Pm, $^{\wedge 234}$Th, $^{\wedge 241}$Am, ^{6}. These findings highlight the critical role of microbial metabolites in governing radionuclide distribution in aquatic and sedimentary environments. Through complexation, redox mediation, and enhanced sorption, microbial biopolymers and siderophores substantially modify radionuclide speciation and mobility, thereby influencing both natural attenuation processes and engineered bioremediation strategies.

High background radiation area associate with radionuclide resistant marine microbial diversity

Several environmentally relevant microorganisms have demonstrated the capacity to interact with radionuclide contaminants through redo mediated and metabolic processes. For example, *Rhodanobacter* and *Desulfuromusa ferrireducens* (formerly reported as *Desulfuromusa ferrireducens*) have been shown to participate in radionuclide transformation via electron transfer reactions[56]. These microorganisms influence radionuclide mobility by mediating oxidation reduction reactions that either donate or accept electrons, thereby altering valence states and modifying solubility and transport behavior[57]. Site specific microbial communities can therefore initiate radionuclide transformation processes that enhance mobilization facilitating flushing or extraction from contaminated systems or promote immobilization through reduction and precipitation pathways. Such bacterially mediated redox transformations represent a critical mechanism for in situ bioremediation strategies, offering the potential either to stabilize radio nuclides within sediments or to enhance their controlled removal from impacted ecosystems[58].

Among radio resistant microorganisms, species belonging to the genus *Deinococcus* have emerged as model organisms for investigating microbial resistance to ionizing radiation (IR). These bacteria exhibit extraordinary tolerance to several kilograys (kGy) of γ-radiation and heavy ion exposure, as well as resistance to ultraviolet radiation, desiccation, and oxidative stress. Remarkably, this resilience occurs despite the absence of unusually large or structurally unique genomes[58]. Instead, resistance is primarily attributed to highly efficient DNA repair systems, robust antioxidant defense mechanisms, and effective protein protection strategies. Unlike many microorganisms that exhibit radiation tolerance primarily during dormant or spore forming stages, *deinococci* maintain extreme resistance in metabolically active vegetative cells. They are capable of sustained growth under prolonged radiation exposure exceeding 100 Gy h^{-1}, suggesting that their DNA repair and cellular recovery mechanisms can operate efficiently under continuous irradiation conditions[59]. This capacity distinguishes *deinococci* as exceptional biological systems for studying cellular adaptation to chronic radiological stress.

Additional microorganisms have also demonstrated the ability to tolerate multiple kilograys of ionizing radiation. Representative examples include members of the genera *Thermococcus*, *Halobacterium*, *Geodermatophilus*, *Kineococcus*, and *Rubrobacter*[60,61]. These taxa exhibit diverse physiological adaptations, including enhanced DNA repair capacity, protective carotenoid pigments, osmotic stabilization systems, and efficient reactive oxygen species (ROS) scavenging pathways. Collectively, these findings underscore the ecological and technological relevance of radioresistant microorganisms in radionuclide contaminated environments. Their metabolic versatility, redox activity, and exceptional stress tolerance provide a biological foundation for advanced remediation strategies under highradiation conditions[63,64,65]. Table-2 summarizes reported mechanisms of microbial radionuclide remediation across different geographic regions worldwide.

Marine microbial diversity are using radioactive remediation

The extent of radiological damage in contaminated environments is governed by the type and intensity of radiation emitted, exposure duration, and the sensitivity of affected biological systems, including humans and ecological receptors[66-68]. Ionizing radiation can alter physicochemical properties of environmental matrices, influencing radionuclide mobility and

bioavailability[70]. Microorganisms, owing to their metabolic adaptability and resilience, possess considerable potential for longterm manipulation in biotechnological remediation applications. Radionuclides are of persistent environmental concern due to their longevity, radiotoxicity, and capacity for bioaccumulation. Natural microbial communities are often the first biological systems to colonize and adapt to contaminated sites. These indigenous microorganisms have been extensively investigated for their suitability in biotechnological applications aimed at radionuclide removal. Localized microbial activity can induce micro environmental changes particularly in pH and redox potential that significantly modify radionuclide solubility and speciation[71], thereby enhancing either immobilization or controlled mobilization.

A notable development in this field is the establishment of "Bio Rad Base," a curated database compiling wildtype and genetically modified microorganisms reported to participate in radionuclide waste remediation[72,73]. The application of microorganisms for radioactive waste management offers several advantages, including: high specificity toward target contaminants, environmental sustainability, operational efficiency, potential for near-complete contaminant removal, reduced economic cost compared to physicochemical treatments, and minimal generation of secondary pollutants[72,73]. Bioaugmentation, defined as the introduction of selected microbial strains to enhance contaminant degradation or immobilization, is widely applied in radionuclide remediation strategies[73]. However, its success depends on the introduced strain's ability to survive, compete, and maintain functional activity under high-radiation and geochemically complex conditions. The persistence and functional stability of microbial consortia remain limiting factors, particularly in marine and sedimentary environments, where indigenous microbial restoration approaches have been debated[74].

Bioremediation strategies for radionuclides commonly include bioaugmentation, biostimulation, biomineralization, and microbially mediated metal reduction. Among these, precipitation and immobilization processes play dominant roles in attenuating radionuclide mobility. For example, modifications of a bio-inorganic ion exchange system demonstrated substantial removal efficiencies of approximately 97% for ^{137}Cs and 85% for ^{60}Co[75]. In that study, a *Serratia sp*. biofilm immobilized using hydrogen uranyl phosphate functioned as a cation exchange matrix. The removal mechanism was primarily governed by cation exchange and intercalation processes within the biofilm structure. Similarly, immobilized alginate beads containing the photosynthetic bacterium *Rhodobacter sphaeroides* achieved 59 to 74% removal of cesium from sediment and silt matrices[76]. These immobilized systems were readily recoverable and maintained removal efficiency over repeated applications, demonstrating their practical viability. However, certain immobilization supports, such as polyurethane foam matrices, have been reported to reduce removal efficiency due to diffusion limitations and structural interference[77].

Overall, microbial systems represent a promising alternative to conventional physicochemical radionuclide remediation technologies. Their effectiveness is rooted in diverse mechanisms, including biosorption, bioaccumulation, redox transformation, biomineralization, and ion exchange. Nevertheless, the full technological potential of microbial radionuclide remediation can only be realized through a comprehensive understanding of microbialradionuclide interactions, ecological adaptability, and process optimization under site-specific conditions.

Challenges and prospects

Microorganisms, particularly bacteria and archaea, represent highly adaptable biological systems capable of surviving and functioning under extreme physicochemical stress, including elevated radiation fields. Their resilience to ionizing radiation, desiccation, oxidative stress, and nutrient limitation underscores their ecological significance and biotechnological potential. Despite their microscopic scale, these organisms drive essential biogeochemical cycles and mediate energy intensive redox transformations that sustain ecosystem stability. Without microbial processes, elemental cycling and environmental homeostasis would be fundamentally disrupted.

Advances in molecular biology, genomics, and synthetic biology have further expanded the scope of microbial applications in radionuclide remediation. Genetic engineering and recombinant technologies enable the enhancement of phenotypic traits such as metal binding capacity, radiation resistance, redox activity, and metabolic efficiency. The interaction between microorganisms and radionuclides, as detailed throughout this review, demonstrates that microbial systems can modulate radionuclide mobility through biosorption, bioaccumulation, biomineralization, biosolubilization, and redox transformation pathways[78].

Recent developments in the application of genetically modified microorganisms for radioactive waste remediation have yielded promising results, particularly in controlled laboratory and pilot-scale studies. However, the strategic use of indigenous microorganisms isolated from radionuclide-contaminated environments such as marine sediments, groundwater systems, and nuclear waste disposal sites may offer greater ecological compatibility and long-term stability. Rigorous characterization of such native strains, including their metabolic versatility, radiation tolerance thresholds, and genetic adaptability, is essential for field scale implementation. Future progress in microbial radionuclide remediation will depend on interdisciplinary collaboration among microbiologists, environmental engineers, geochemists, radiation biologists, and materials scientists. Integration of omics-based technologies, advanced bioreactor design, and systems modeling will enhance process optimization and scalability. When fully developed, microbial consortia or engineered strains could be deployed for

large-scale remediation of radioactive wastes, either in situ or ex situ[79].

Table-2: Microbial and Biotechnological Strategies for Radioisotope Decontamination.

Mode of Decontamination	Microorganism(s)	Target Radioisotope(s) (Initial Concentration)	Reference
Biosorption / Bioaccumulation / Biotransformation	*Mucor circinelloides*	U(VI) (30 mg L^{-1})	60
Phytoremediation / Bioaccumulation	*Ludwigia stolonifera*	^{60}Co (100 Bq)	61
Biosorption / Biomineralization	*Saccharomyces cerevisiae*	U(VI) (10 mg L^{-1})	62
Biosorption / Biotransformation	*Desulfovibrio desulfuricans*	U(VI) (50 µmol L^{-1}) + Fe^{2+}	63
Enzymatic Reduction	*Geobacter sulfurreducens; Clostridium sp.; Shewanella*	U(VI)	64
Biotransformation / Biosorption / Bioaccumulation	*Pseudomonas mendocina; Bacillus subtilis; Arthrobacter spp*.	Pb (II), Zn (II), Cd (II), Sr (II), Th (IV), U(IV)	65
Biodegradation of chelators / Volatilization / Treatment trains / Natural attenuation	*Deinococcus radiodurans R1; Escherichia coli; Ralstonia eutropha; Arthrobacter ilicis*	Uranyl phosphate; uranyl nitrate; Co; Hg (II)	66
Surface-associated uranium precipitation (5.7 g U g^{-1} biomass)	*Deinococcus radiodurans*	Uranium	67
Recombinant strain achieving 85% cobalt removal (two-cycle treatment)	*Rhodopseudomonas* palustris CGA0009	Cobalt	68
Recombinant strain precipitating >90% of 0.5–5 mM uranyl carbonate (<2 h)	*Sphingomonas sp.* BSAR-1	Uranium	69
Recombinant strain precipitating >90% of 0.8 mM uranyl nitrate (6 h)	*Salmonella enterica* serovar *Typhi*	Uranium	70

An additional advantage of microbial remediation lies in its potential for resource recovery. Extracted radionuclides may be recovered and repurposed for industrial, medical, or energy related applications under controlled conditions. Moreover, microbial systems are inherently renewable and can often be reused through regeneration or immobilization strategies, thereby reducing operational costs and environmental impact. In conclusion, microbialbased radionuclide remediation represents a sustainable, environmentally compatible alternative to conventional physicochemical treatment methods. A comprehensive understanding of microbial radionuclide interactions, combined with advances in biotechnology and environmental engineering, will be pivotal in unlocking the full potential of these biological systems for safe and efficient radioactive waste management[80].

Conclusion

Marine microbial radionuclide transformations constitute a critical component of natural biogeochemical processes within the biosphere, particularly in environments characterized by high background radiation areas (HBRA). In such systems, complex interactions occur at the microberadionuclide interface, governed by physicochemical gradients, redox dynamics, salinity, and sediment water exchange processes. Elucidating these interactions remains challenging due to the diversity of marine habitats and the adaptive strategies employed by resident microbial communities. A comprehensive understanding of the molecular and metabolic mechanisms underlying microbial radionuclide transformation is essential for advancing remediation technologies. Key processes including bioaccumulation, biosorption, biotransformation, biosolubilization, and bioprecipitation collectively regulate radionuclide speciation, mobility, and long-term environmental fate. These mechanisms are mediated by specific cellular structures, extracellular polymeric substances, enzymatic redox systems, and metabolite production, which together determine radionuclide partitioning between dissolved and solid phases.

Deciphering these molecular pathways will not only clarify the ecological role of marine microorganisms in radionuclide cycling but also facilitate the identification of microbial metabolites suitable for cellfree or enzyme assisted bioremediation systems. Such approaches may enable efficient and targeted removal of radionuclides from marine and coastal ecosystems while minimizing secondary environmental impacts. Overall, integrating molecular microbiology, marine geochemistry, and environmental biotechnology will be crucial for translating fundamental insights into practical remediation strategies in HBRA and other radionuclide impacted marine environments.

References

1. Popic, J. M., Urso, L., & Michalik, B. (2023). Assessing the exposure situations with naturally occurring radioactive

materials across European countries by means of the e-NORM survey. *Science of the total Environment*, 905, 167065.

2. Pandion, K., Arunachalam, K. D., Dowlath, M. J. H., Chinnapan, S., Chang, S. W., Chang, W., ... & Ravindran, B. (2023). The spatial distribution of physicochemical parameters in coastal sediments along the Bay of Bengal Coastal Zone with statistical analysis. *Environmental Monitoring and Assessment*, 195(1), 126.

3. Acosta-González, A., & Marqués, S. (2016). Bacterial diversity in oil-polluted marine coastal sediments. *Current opinion in biotechnology*, *38*, 24-32.

4. Cecchi, G., Cutroneo, L., Di Piazza, S., Vagge, G., Capello, M., & Zotti, M. (2020). From waste to resource: mycoremediation of contaminated marine sediments in the SEDITERRA project. *Journal of soils and sediments*, 20(6), 2653-2663.

5. Bulgariu, L., & Bulgariu, D. (2019). Bioremediation of toxic heavy metals using marine algae biomass. In *Green materials for wastewater treatment* (pp. 69-98). Cham: Springer International Publishing.

6. Trevisi, R., Ampollini, M., Bogi, A., Bucci, S., Caldognetto, E., La Verde, G., ... & Pugliese, M. (2023). Radiological protection in industries involving NORM: a (graded) methodological approach to characterize the exposure situations. *Atmosphere*, 14(4), 635.

7. Sohrabi, M. (2013). World high background natural radiation areas: Need to protect public from radiation exposure. *Radiation Measurements*, 50, 166-171.

8. Xiong, D., & Wang, C. (2021). Risk assessment of human exposure to heavy metals, polycyclic aromatic hydrocarbons, and radionuclides in oil-based drilling cutting residues used for roadbed materials in Chongqing, China. *Environmental Science and Pollution Research*, 28(35), 48171-48183.

9. Puertas, F., Suárez-Navarro, J. A., Alonso López, M., & Gascó, C. (2021). NORM waste, cements, and concretes. A review.

10. Popic, J. M., Haanes, H., Di Carlo, C., Nuccetelli, C., Venoso, G., Leonardi, F., ... & Fevrier, L. (2023). Tools for harmonized data collection at exposure situations with naturally occurring radioactive materials (NORM). *Environment International*, 175, 107954.

11. Julius, H. W., & Van Dongen, R. (1985). Radiation doses to the population in the Netherlands, due to external natural sources. *Science of The Total Environment*, 45, 449-458.

12. Green, B. M. R., Brown, L., Cliff, K. D., Driscoll, C. M. H., Miles, J. C. H., & Wrixon, A. D. (1985). Surveys of natural radiation exposure in UK dwellings with passive and active measurement techniques. *Science of the Total Environment*, 45, 459-466.

13. Bezuidenhout, J., & le Roux, R. (2024). Investigating Radon Concentrations in the Cango Cave, South Africa. *Atmosphere*, 15(9), 1133.

14. Lin, Y. M., Lin, P. H., Chen, C. J., & Huang, C. C. (1987). Measurements of terrestrial γ radiation in Taiwan, Republic of China. *Health physics* (1958), 52(6), 805-811.

15. Tso, M. Y. W., & Li, C. C. (1992). Terrestrial gamma radiation dose in Hong Kong. *Health physics*, 62(1), 77-81.

16. Marouf, B. A., Mohamad, A. S., Taha, J. S., & Al-Haddad, I. K. (1992). Population doses from environmental gamma radiation in Iraq. *Health physics*, 62(5), 443-444.

17. Al-Jundi, J. (2002). Population doses from terrestrial gamma exposure in areas near to old phosphate mine, Russaifa, Jordan. *Radiation Measurements*, 35(1), 23-28.

18. Aliyu, A. S., & Ramli, A. T. (2015). The world's high background natural radiation areas (HBNRAs) revisited: A broad overview of the dosimetric, epidemiological and radiobiological issues. *Radiation Measurements*, 73, 51-59.

19. Ahmad, S., Koya, P. K. M., & Seshadri, M. (2013). Effects of chronic low level radiation in the population residing in the high level natural radiation area in Kerala, India: employing heritable DNA mutation studies. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 751(2), 91-95.

20. Karuppasamy, C. V., Ramachandran, E. N., Kumar, V. A., Kumar, P. V., Koya, P. K. M., Jaikrishan, G., & Das, B. (2016). Peripheral blood lymphocyte micronucleus frequencies in men from areas of Kerala, India, with high vs normal levels of natural background ionizing radiation. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 800, 40-45.

21. Singh, H. N., Shanker, D., Neelakandan, V. N., & Singh, V. P. (2007). Distribution patterns of natural radioactivity and delineation of anomalous radioactive zones using in situ radiation observations in Southern Tamil Nadu, India. *Journal of hazardous materials*, 141(1), 264-272.

22. Bhattacharya, T., Shankar, V. M., Reddy, B. R. M., Thangavel, S., & Sharma, P. K. (2018). Radioactivity levels in the atomic mineral occurrences along Dharmapuri Shear zone in parts of Vellore, Krishnagiri, Dharmapuri and Salem districts of Tamil Nadu, India. *Applied Radiation and Isotopes*, 132, 135-141.

23. K., Bhaumik, B. K., Guin, R., & Saha, S. K. (2006). A new high background radiation area in the Geothermal region of Eastern Ghats Mobile Belt (EGMB) of Orissa, India. *Radiation Measurements*, 41(5), 602-610.

24. Mohanty, A. K., Sengupta, D., Das, S. K., Saha, S. K., & Van, K. V. (2004). Natural radioactivity and radiation exposure in the high background area at Chhatrapur beach placer deposit of Orissa, India. *Journal of environmental radioactivity*, 75(1), 15-33.

25. Shrivastava, H. B., Rao, V. K., Singh, R. V., Rahman, M., Rout, G. B., Banerjee, R., ... & Verma, M. B. (2015). Uranium series disequilibrium studies in Chenchu colony area, Guntur district, Andhra Pradesh, India. *Applied Radiation and Isotopes*, 105, 163-169.

26. Reddy, K. V. K., Reddy, B. S., Reddy, M. S., Reddy, C. G., Reddy, P. Y., & Reddy, K. R. (2003). Baseline studies of radon/thoron concentration levels in and around the Lambapur and Peddagattu areas in Nalgonda district, Andhra Pradesh, India. *Radiation measurements*, 36(1-6), 419-423.

27. Mulas, D., Camacho, A., Serrano, I., Montes, S., Devesa, R., & Duch, M. A. (2017). Natural and artificial radionuclides in sludge, sand, granular activated carbon and reverse osmosis brine from a metropolitan drinking water treatment plant. *Journal of environmental radioactivity*, 177, 233-240.

28. Tsytsugina, V. G. E., Risik, N. S., Lazorenko, G. E., & Polikarpov, B. (1975). Artificial and natural radionuclides in marine life.

29. Veguería, S. F. J., Godoy, J. M., & Miekeley, N. (2002). Environmental impact in sediments and seawater due to discharges of Ba, 226Ra, 228Ra, V, Ni and Pb by produced water from the Bacia de Campos oil field offshore platforms. *Environmental Forensics*, 3(2), 115-123.

30. Vegueria, S. J., Godoy, J. M., & Miekeley, N. (2002). Environmental impact studies of barium and radium discharges by produced waters from the "Bacia de Campos" oil-field offshore platforms, Brazil. *Journal of Environmental radioactivity*, 62(1), 29-38.

31. Matishov, D. G., & Matishov, G. G. (2013). *Radioecology in Northern European Seas*. Springer Science & Business Media.

32. Harikrishnan, N., Ravisankar, R., Chandrasekaran, A., Gandhi, M. S., Vijayagopal, P., & Mehra, R. (2018). Assessment of gamma radiation and associated radiation hazards in coastal sediments of south east coast of Tamilnadu, India with statistical approach. *Ecotoxicology and Environmental safety*, 162, 521-528.

33. Ramasamy, V., Sundarrajan, M., Paramasivam, K., Meenakshisundaram, V., & Suresh, G. (2013). Assessment of spatial distribution and radiological hazardous nature of radionuclides in high background radiation area, Kerala, India. *Applied Radiation and Isotopes*, 73, 21-31.

34. Noureddine, A., Benkrid, M., Hammadi, A., Boudjenoun, R., Menacer, M., Khaber, A., & Kecir, M. S. (2003). Radioactivity distribution in surface and core sediment of the central part of the Algerian Coast: An estimation of the recent sedimentation rate. *Mediterranean Marine Science*, 4(2), 53-58.

35. Berlanga, M. (2000). Microbiología. LM Prescott, JP Harley, DA Klein. *International Microbiology*, 3(3), 198-199.

36. Tamponnet, C., Martin-Garin, A., Gonze, M. A., Parekh, N., Vallejo, R., Sauras-Yera, T., ... & Shaw, G. (2008). An overview of BORIS: bioavailability of radionuclides in soils. *Journal of Environmental Radioactivity*, 99(5), 820-830.

37. Shaowei, W., Zhaorong, S., Ping, W., Guoliang, W., & Yuqin, D. (2016). Study on radioactive contaminated soil remediation technologies and selection principles. In *International Confernece Pacific Basin Nuclear Conference* (pp. 547-554). Singapore: Springer Singapore.

38. Tabak, H. H., Lens, P., Van Hullebusch, E. D., & Dejonghe, W. (2005). Developments in bioremediation of soils and sediments polluted with metals and radionuclides–1. Microbial processes and mechanisms affecting bioremediation of metal contamination and influencing metal toxicity and transport. *Reviews in Environmental Science and Bio/Technology*, 4(3), 115-156.

39. Tišáková, L. E. N. K. A., Pipíška, M. A. R. T. I. N., Godány, A. N. D. R. E. J., Horník, M. I. R. O. S. L. A. V., Vidová, B., & Augustín, J. (2013). Bioaccumulation of ^{137}Cs and ^{60}Co by bacteria isolated from spent nuclear fuel pools. *Journal of Radioanalytical and Nuclear Chemistry*, 295(1), 737-748.

40. Staunton, S., Dumat, C., & Zsolnay, A. (2002). Possible role of organic matter in radiocaesium adsorption in soils. *Journal of Environmental Radioactivity*, 58(2-3), 163-173.

41. Merroun, M. L., & Selenska-Pobell, S. (2008). Bacterial interactions with uranium: an environmental perspective. *Journal of Contaminant Hydrology*, 102(3-4), 285-295.

42. Ozdemir, S., Oduncu, M. K., Kilinc, E., & Soylak, M. (2017). Resistance, bioaccumulation and solid phase extraction of uranium (VI) by Bacillus vallismortis and its UV–vis spectrophotometric determination. *Journal of environmental radioactivity*, 171, 217-225.

43. Tsuruta, T. (2006). Bioaccumulation of uranium and thorium from the solution containing both elements using various microorganisms. *Journal of alloys and compounds*, 408, 1312-1315.

44. Prakash, D., Gabani, P., Chandel, A. K., Ronen, Z., & Singh, O. V. (2013). Bioremediation: a genuine technology to remediate radionuclides from the environment. *Microbial Biotechnology*, 6(4), 349-360.

45. Luk'yanova, E. A., Zakharova, E. V., Konstantinova, L. I., & Nazina, T. N. (2008). Sorption of radionuclides by microorganisms from a deep repository of liquid low-level waste. *Radiochemistry*, 50(1), 85-90.

46. Dobrowolski, R., Szcześ, A., Czemierska, M., & Jarosz-Wikołazka, A. (2017). Studies of cadmium (II), lead (II),

nickel (II), cobalt (II) and chromium (VI) sorption on extracellular polymeric substances produced by Rhodococcus opacus and Rhodococcus rhodochrous. *Bioresource technology*, 225, 113-120.

47. Jabbar, T., & Wallner, G. (2015). Biotransformation of radionuclides: Trends and challenges. *Radionuclides in the Environment: Influence of chemical speciation and plant uptake on radionuclide migration*, 169-184.

48. Francis, A. J., & Nancharaiah, Y. V. (2015). In situ and ex situ bioremediation of radionuclide-contaminated soils at nuclear and norm sites. In *Environmental remediation and restoration of contaminated nuclear and norm sites* (pp. 185-236). Woodhead Publishing.

49. Mohapatra, B. R., Dinardo, O., Gould, W. D., & Koren, D. W. (2010). Biochemical and genomic facets on the dissimilatory reduction of radionuclides by microorganisms –A review. *Minerals Engineering*, 23(8), 591-599.

50. Cherkouk, A., Law, G. T., Rizoulis, A., Law, K., Renshaw, J. C., Morris, K., ... & Lloyd, J. R. (2016). Influence of riboflavin on the reduction of radionuclides by Shewanella oneidenis MR-1. *Dalton Transactions*, 45(12), 5030-5037.

51. Pandey, B. D., & Natarajan, K. A. (Eds.). (2015). Microbiology for minerals, metals, materials and the environment. CRC Press.

52. Francis, A. J., Dodge, C. J., & Gillow, J. B. (1992). Biodegradation of metal citrate complexes and implications for toxic-metal mobility. *Nature*, 356(6365), 140-142.

53. Dadachova, E., & Casadevall, A. (2008). Ionizing radiation: how fungi cope, adapt, and exploit with the help of melanin. *Current opinion in microbiology*, 11(6), 525-531.

54. Arlinger, J., Oskarsson, A., Albinsson, Y., Andlid, T., & Pedersen, K. (2003). Mobilisation of radionuclides by ligands produced by bacteria from the deep subsurface. *MRS Online Proceedings Library (OPL)*, 807, 823.

55. Green, S. J., Prakash, O., Jasrotia, P., Overholt, W. A., Cardenas, E., Hubbard, D., ... & Kostka, J. E. (2012). Denitrifying bacteria from the genus Rhodanobacter dominate bacterial communities in the highly contaminated subsurface of a nuclear legacy waste site. *Applied and environmental microbiology*, *78*(4), 1039-1047.

56. Amachi, S., Minami, K., Miyasaka, I., & Fukunaga, S. (2010). Ability of anaerobic microorganisms to associate with iodine: 125I tracer experiments using laboratory strains and enriched microbial communities from subsurface formation water. *Chemosphere*, 79(4), 349-354.

57. Sharma, A., Gaidamakova, E. K., Grichenko, O., Matrosova, V. Y., Hoeke, V., Klimenkova, P., ... & Daly, M. J. (2017). Across the tree of life, radiation resistance is governed by antioxidant Mn^{2+}, gauged by paramagnetic resonance. *Proceedings of the National Academy of Sciences*, 114(44), E9253-E9260.

58. Shuryak, I., & Brenner, D. J. (2010). Effects of radiation quality on interactions between oxidative stress, protein and DNA damage in Deinococcus radiodurans. *Radiation and environmental biophysics*, 49(4), 693-703.

59. Ardini, M., Fiorillo, A., Fittipaldi, M., Stefanini, S., Gatteschi, D., Ilari, A., & Chiancone, E. (2013). Kineococcus radiotolerans Dps forms a heteronuclear Mn–Fe ferroxidase center that may explain the Mn-dependent protection against oxidative stress. *Biochimica et Biophysica Acta (BBA)-General Subjects*, 1830(6), 3745-3755.

60. Song, S., Zhang, S., Huang, S., Zhang, R., Yin, L., Hu, Y., ... & Wang, X. (2019). A novel multi-shelled Fe3O4@ MnOx hollow microspheres for immobilizing U (VI) and Eu (III). *Chemical Engineering Journal*, 355, 697-709.

61. Slade, D., & Radman, M. (2011). Oxidative stress resistance in Deinococcus radiodurans. *Microbiology and molecular biology reviews*, *75*(1), 133-191.

62. Yu, K. N., Stokes, M. J., Young, E., & Guan, Z. J. (1994). Natural and artificial radionuclides in seabed sediments of Hong Kong. *Nuclear Geophysics (International Journal of Radiation Applications and Instrumentation, Part E);(United Kingdom)*, 8(1).

63. Ding, L., Tan, W. F., Xie, S. B., Mumford, K., Lv, J. W., Wang, H. Q., ... & Li, M. (2018). Uranium adsorption and subsequent re-oxidation under aerobic conditions by Leifsonia sp.-Coated biochar as green trapping agent. *Environmental Pollution*, 242, 778-787.

64. Lovley, D. R. (2002). Microbial redox interactions with uranium: an environmental perspective. In *Radioactivity in the Environment* (Vol. 2, pp. 205-223). Elsevier.

65. Yin, Y., Wang, J., Yang, X., & Li, W. (2017). Removal of strontium ions by immobilized Saccharomyces cerevisiae in magnetic chitosan microspheres. *Nuclear Engineering and Technology*, 49(1), 172-177.

66. Alexandrova, M., Rozhko, T., Vydryakova, G., & Kudryasheva, N. (2011). Effect of americium-241 on luminous bacteria. Role of peroxides. *Journal of environmental radioactivity*, *102*(4), 407-411.

67. Misra, C. S., Appukuttan, D., Kantamreddi, V. S. S., Rao, A. S., & Apte, S. K. (2012). Recombinant D. radiodurans cells for bioremediation of heavy metals from acidic/neutral aqueous wastes. *Bioengineered*, 3(1), 44-48.

68. Raghu, G., Balaji, V., Venkateswaran, G., Rodrigue, A., & Maruthi Mohan, P. (2008). Bioremediation of trace cobalt from simulated spent decontamination solutions of nuclear power reactors using E. coli expressing NiCoT genes. *Applied microbiology and biotechnology*, 81(3), 571-578.

69. Nilgiriwala, K. S., Alahari, A., Rao, A. S., & Apte, S. K. (2008). Cloning and overexpression of alkaline phosphatase PhoK from Sphingomonas sp. strain BSAR-1 for

bioprecipitation of uranium from alkaline solutions. *Applied and environmental microbiology*, 74(17), 5516-5523.

70. Appukuttan, D., Rao, A. S., & Apte, S. K. (2006). Engineering of Deinococcus radiodurans R1 for bioprecipitation of uranium from dilute nuclear waste. *Applied and Environmental Microbiology*, 72(12), 7873-7878.

71. Hazen, T. C., & Tabak, H. H. (2005). Developments in bioremediation of soils and sediments polluted with metals and radionuclides: 2. Field research on bioremediation of metals and radionuclides. *Reviews in Environmental Science and Bio/Technology*, 4(3), 157-183.

72. Reena, R., Majhi, M. C., Arya, A. K., Kumar, R., & Kumar, A. (2012). BioRadBase: a database for bioremediation of radioactive waste. *African Journal of Biotechnology*, 11(35), 8718-8721.

73. Xu, Y., & Zhou, N. Y. (2017). Microbial remediation of aromatics-contaminated soil. *Frontiers of Environmental Science & Engineering*, 11(2), 1.

74. Lofrano, G., Libralato, G., Minetto, D., De Gisi, S., Todaro, F., Conte, B., ... & Notarnicola, M. (2017). In situ remediation of contaminated marinesediment: an overview. *Environmental Science and Pollution Research*, 24(6), 5189-5206.

75. Paterson-Beedle, M., Macaskie, L. E., Lee, C. H., Hriljac, J. A., Jee, K. Y., & Kim, W. H. (2006). Utilisation of a hydrogen uranyl phosphate-based ion exchanger supported on a biofilm for the removal of cobalt, strontium and caesium from aqueous solutions. *Hydrometallurgy*, 83(1-4), 141-145.

76. Sasaki, K., Takeno, K., Shinkawa, H., Sasaki, K., & Das, N. (2015). Removal of radioactivity and recovery of radioactive Cs from sediment mud and soil in Fukushima, Japan using immobilized photosynthetic bacteria. *Advanced Materials Research*, 1091, 125-130.

77. Pandion, K., & Arunachalam, K. D. (2022). Potential health risk estimation of naturally occurring radionuclides intake due to the consumption of seafood around Coastal zone. *J. Food Sci. Nutr. Ther.*, 8(1), 028-037.

78. Pandion, K., Dowlath, M. J. H., Arunachalam, K. D., Abd-Elkader, O. H., Yadav, K. K., Nazir, N., ... & Ravindran, B. (2023). Seasonal influence on physicochemical properties of the sediments from Bay of Bengal coast with statistical approach. *Environmental Research*, 235, 116611.

79. Pandion, K., Mayanib, S. V., Nikamc, R. J., Saranb, A., & Deivi Arunachalam, K. (2024). Naturally occurring radionuclides intake of fish diversity by inhabitants around the nuclear power plant, based on the market basket sampling (MBS) approach. *Environ. Sci. Open Access*, 2(1), 1006.

80. Pandion, K., Arunachalam, K. D., Gaafar, A. R. Z., Almunqedhi, B. M., Kuppusamy, S., Singh, R. P., ... & Balasubramani, R. (2025). Assessment of naturally occurring radionuclides in the coastal sediment with statistical analysis of radiological risk parameters. *Journal of Hydroinformatics*, 27(1), 17-32.